# Project Summary of the 2-micron ACLAIM Lidar on the NASA DC-8


**Edward H. Teets Jr.,**
**NASA Dryden Flight Research Center**

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# Contributors

**L. J. Ehernberger, and Rodney K. Bogue**
NASA Dryden Flight Research Center, Edwards, CA

**Christopher E. Ashburn**
AS&M, Edwards, CA

**Philip Gatt and Sara C. Tucker**
Coherent Technologies, Inc., Lafayette, CO

**Gary W. Grew, Philip Brockman, and Ivan O. Clark**
NASA Langley Research Center, Hampton, VA

**Carroll W. Rowland**
Swales Aerospace, Hampton, VA

# Project Summary of the 2-micron ACLAIM Lidar on the NASA DC-8

## Introduction

- Turbulence encounter trends
- Objectives
- DC-8 Lidar turbulence detection installation
- Fourth Convection and Moisture Experiment (CAMEX-4)
- Gust / Cloud penetration sample
- Example lidar line-of-sight velocity data
- ACLAIM 2-micron backscatter experience

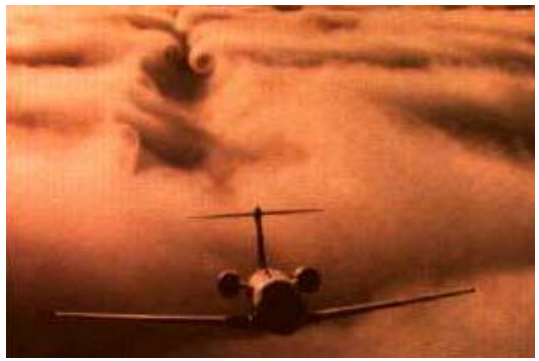
# Sources of Turbulence


Convective Induced

Mountain-wave Induced

Jet-stream Induced

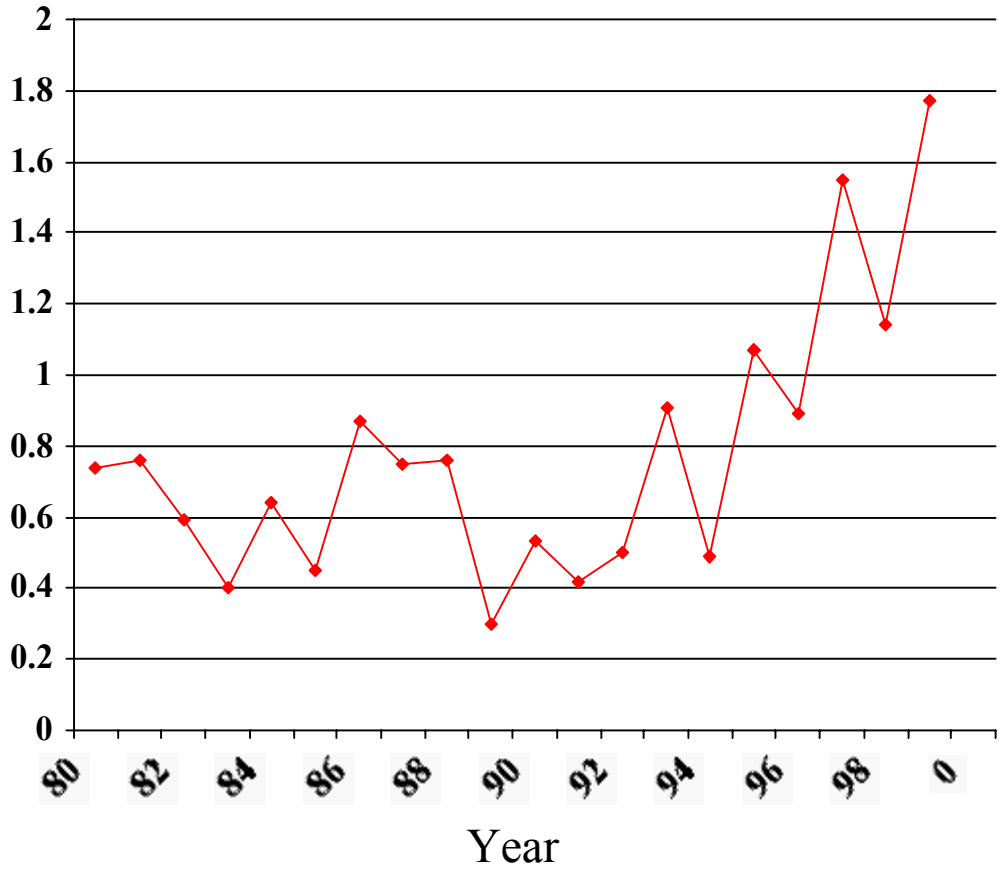
Kelvin-Helmholtz



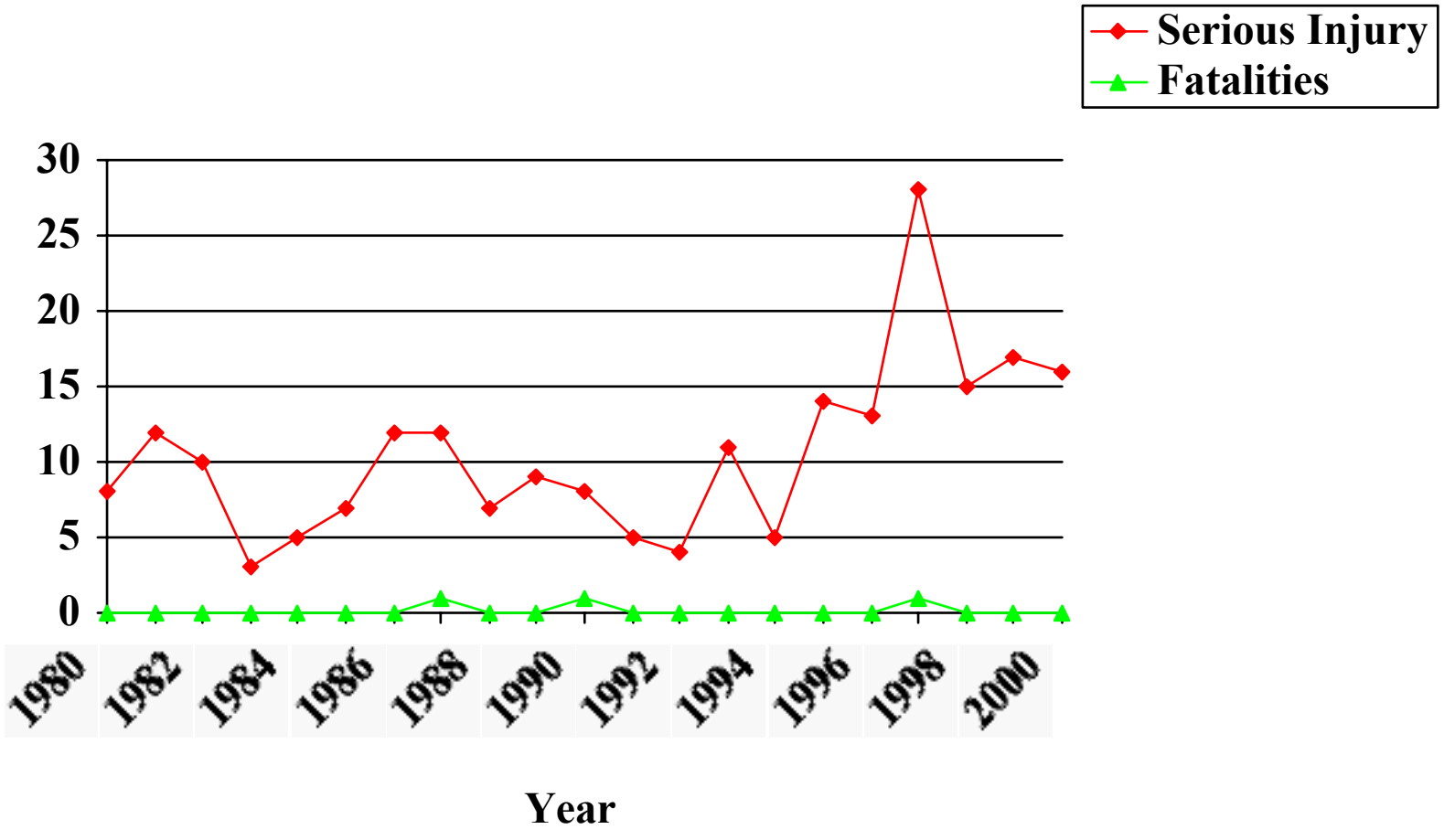
Enroute Wake Vortex

# Turbulence Accident Trends

**Turbulence Accidents per Million Flights US Carriers, Based on Part 121 Definition**



# Serious/Fatal Turbulence Injury History



# Objectives

- To obtain operational experience in high moisture environment with large backscatter variations from a variety of clouds, clear-air and very clean air

- Assess performance near cloud entry and exit

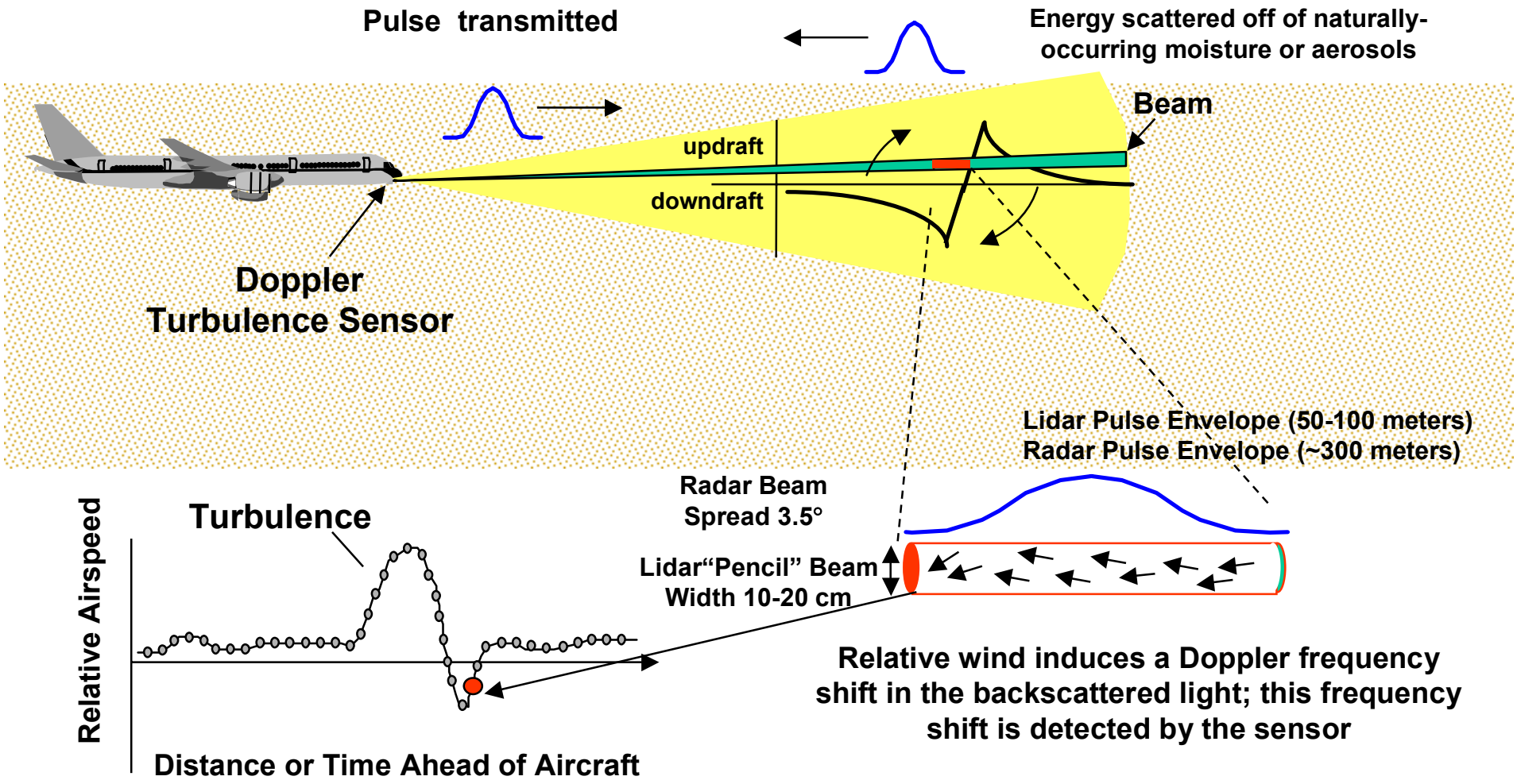
- Evaluate range of detection of light to moderate turbulence

- Validate Lidar wind shear measurement capability

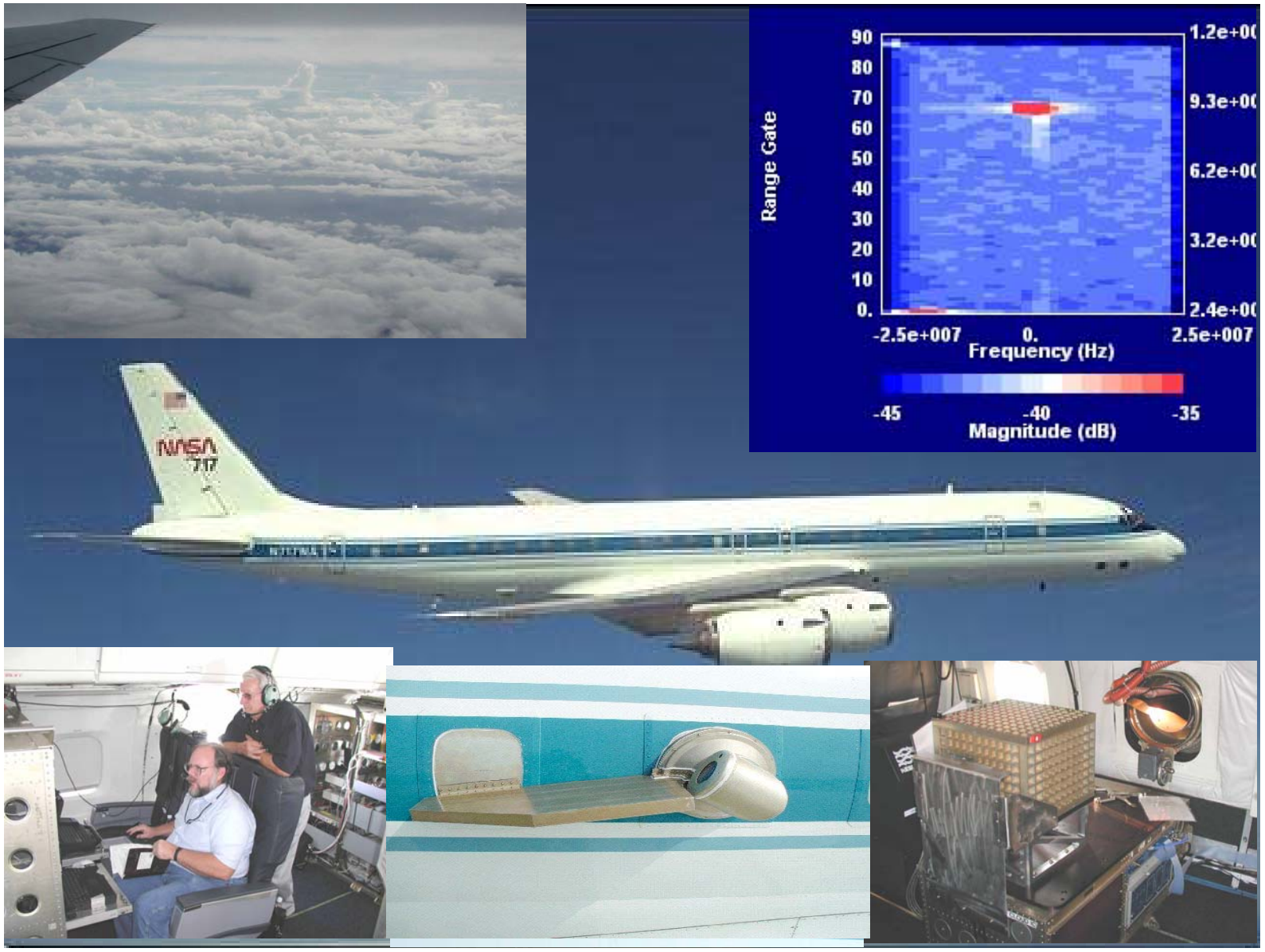
- Validate atmosphere backscatter design model

- Demonstrate Lidar functionality at cruise speed and altitude

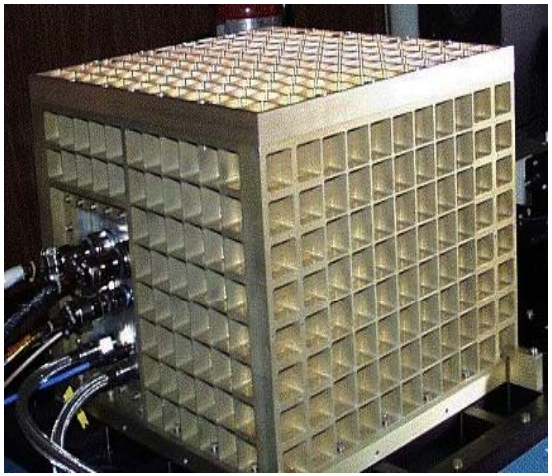
# General Principle of Doppler Radar/Lidar Turbulence Measurement

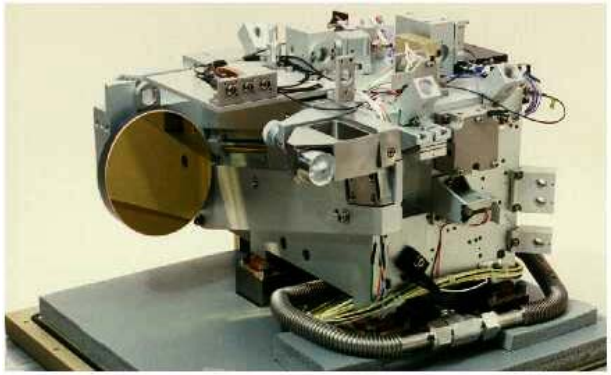


# Airborne Coherent Lidar for Advanced In-Flight Measurements (ACLAIM) CAMEX-4 Flight Tests



# DC-8 Lidar Hardware and Specifications

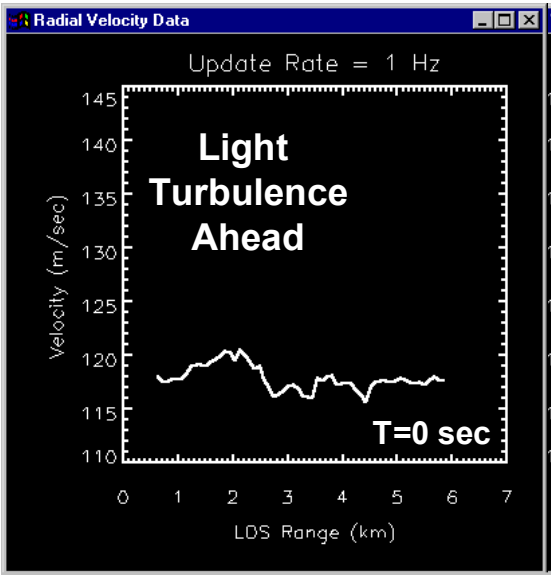


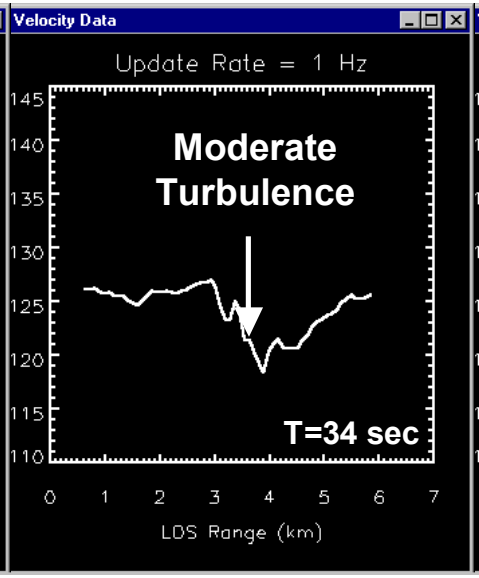


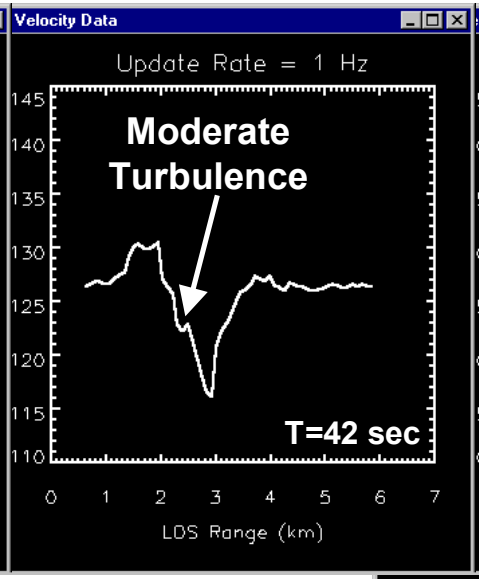
**Current Nominal ACLAIM Sensor Specifications**

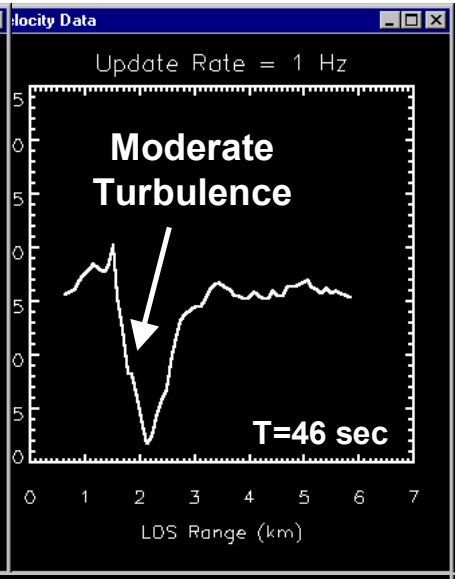
| Parameter | Value |
|---|---|
| Wavelength, $\lambda$ | 2012.5 nm. |
| System efficiency, $\eta$ | 14.5 % |
| Pulse Energy, Ex | ~ 8 mJ |
| Pulse duration | 550 ns |
| Telescope diameter, 2a | 10 cm |
| TEM00 beam diameter, $D_b = 2\ \omega_o$ | 8 cm |
| Focal length, F | 2 km |
| Pulse repetition frequency (PRF) | 100 Hz |

# Electra LIDAR Airspeed Results in Turbulence Encounter

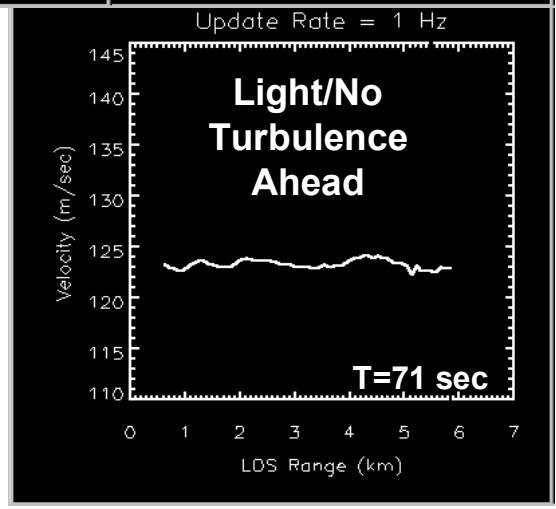


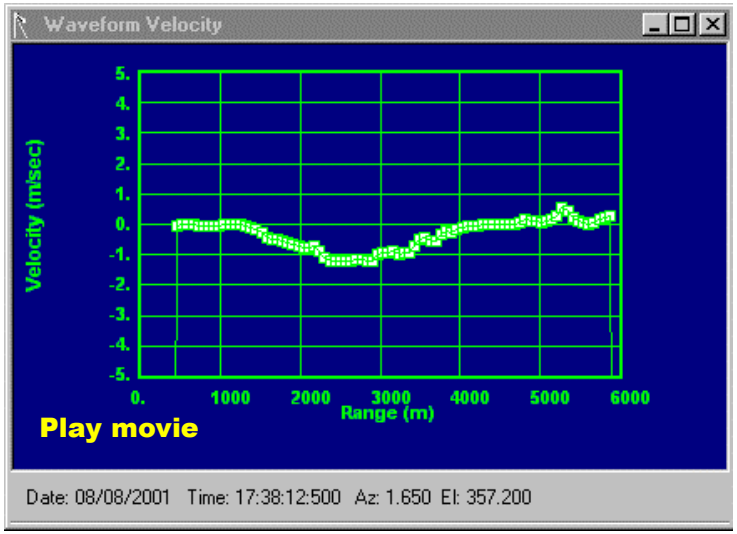

- ”Isolated” moderate turbulence region in light turbulence
- Detected ahead and observed as aircraft approached
- Moderate turbulence observed aboard aircraft (25 sec later)
- Aircraft traversed through turbulence and into smoother air

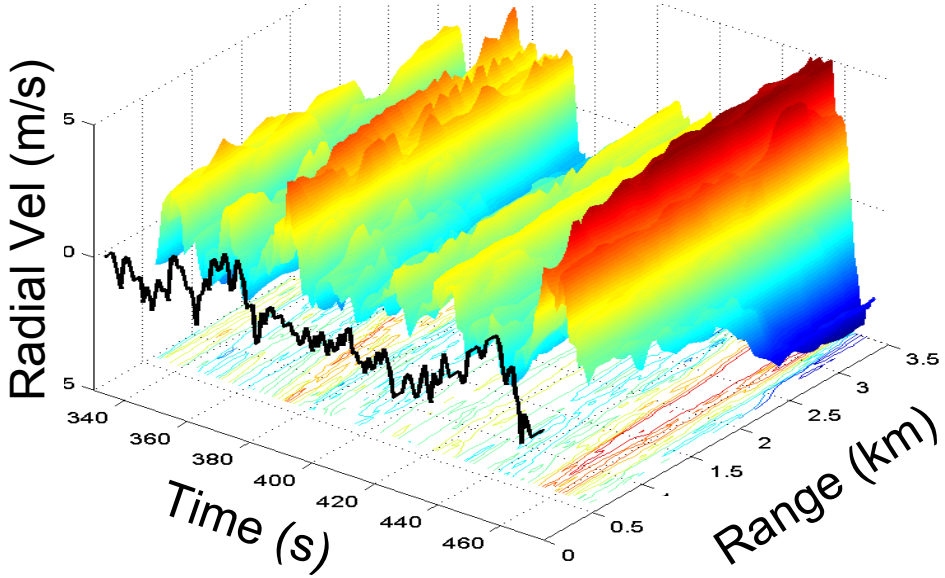


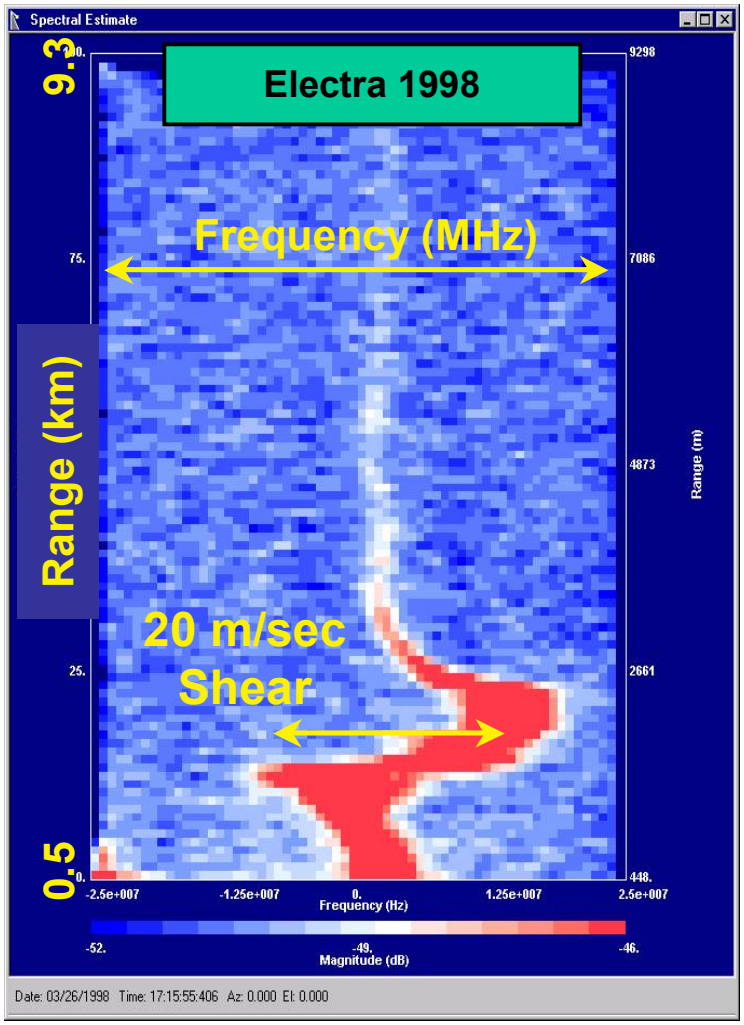

**Sample Turbulence Encounter**

# ACLAIM Data: CAMEX-IV and Electra

**CAMEX –IV 2001**



# CAMEX-4 Data Analysis Examples

3 Cases:

- August 25, 2001 Forward looking
  - Strong signal with large vertical acceleration

- September 10, 2001 Upward, Forward and Down looking
  - Wind shear measurement
  - Signal return in smooth air
  - Cloud and ocean surface returns

- September 19, 2001 Forward looking
  - Good prediction of gust

# Camex-4 Flight Summary

| ACLAIM CAMEX-4 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Flight | DC-8 Flight# | Date | Flight Duration | Flight Type | Target | Other A/C | Data (GB) | Data (CDs) |
| ICF1 | | 8/3/2001 | | ICF | | - | 1.0 | 3 |
| ICF2 | | 8/8/2001 | | ICF | | - | 2.0 | 5 |
| 1 | 01-04-06 | 8/18/2001 | 5 | | Andros Island | ER2 | 7.6 | 15 |
| 2 | 01-04-07 | 8/20/2001 | 8 | CAMEX | Chantal | ER2 | 8.9 | 17 |
| 3 | 01-04-08 | 8/25/2001 | 2 | ICF | buoy off Cape Kennedy | | 5.0 | 10 |
| 4 | 01-04-09 | 9/3/2001 | 5 | KAMP | Keys | ER2, P3 | 8.0 | 16 |
| 5 | 01-04-10 | 9/6/2001 | 2 | KAMP | Keys / TRM | | 7.1 | 13 |
| 6 | 01-04-11 | 9/7/2001 | 5 | KAMP | Tampa - Gulf | ER2 | 11.0 | 20 |
| 7 | 01-04-12 | 9/9/2001 | 5 | KAMP | Keys | | 11.0 | 20 |
| 8 | 01-04-13 | 9/10/2001 | 8.5 | CAMEX | Erin | | 18.2 | 35 |
| 9 | 01-04-14 | 9/15/2001 | 6.5 | CAMEX | Gabrielle | | 16.0 | 29 |
| 10 | 01-04-15 | 9/19/2001 | 5 | KAMP | Keys | | 12.0 | 22 |
| 11 | 01-04-16 | 9/22/2001 | 8 | CAMEX | Humberto | ER2, P3 | 20.1 | 37 |
| 12 | 01-04-17 | 9/23/2001 | 8 | CAMEX | Humberto | ER2, P3 +3 | 19.7 | 36 |
| 13 | 01-04-18 | 9/24/2001 | 8.25 | CAMEX | Humberto | ER2, P3 | 21.9 | 40 |
| | | | 76.3 | | | | 169.6 | 318 |

# Preliminary Tabulation of CAMEX-4 Turbulence Encounters

| Date 2001 | > MDT | > LGT to MDT | > LGT |
|---|---|---|---|
| Aug. 18 | 2 | 3 | 3 |
| Aug. 20 | 1 | 1 | 3 |
| Aug. 25 | 1 | 1 | 3 |
| Sept. 3 | | 1 | 2 |
| Sept. 6 | | 1 | 3 |
| Sept. 7 | | 2 | 6 |
| Sept. 9 | | 3 | 5 |
| Sept. 10 | | | |
| Sept. 15 | 1 | 3 | 5 |
| Sept. 19 | 2 | 5 | 7 |
| Sept. 22 | 1 | 5 | 9 |
| Sept. 23 | 1 | 3 | 3 |
| Sept. 24 | 1 | 3 | 5 |
| Total | 10 | 31 | 54 |

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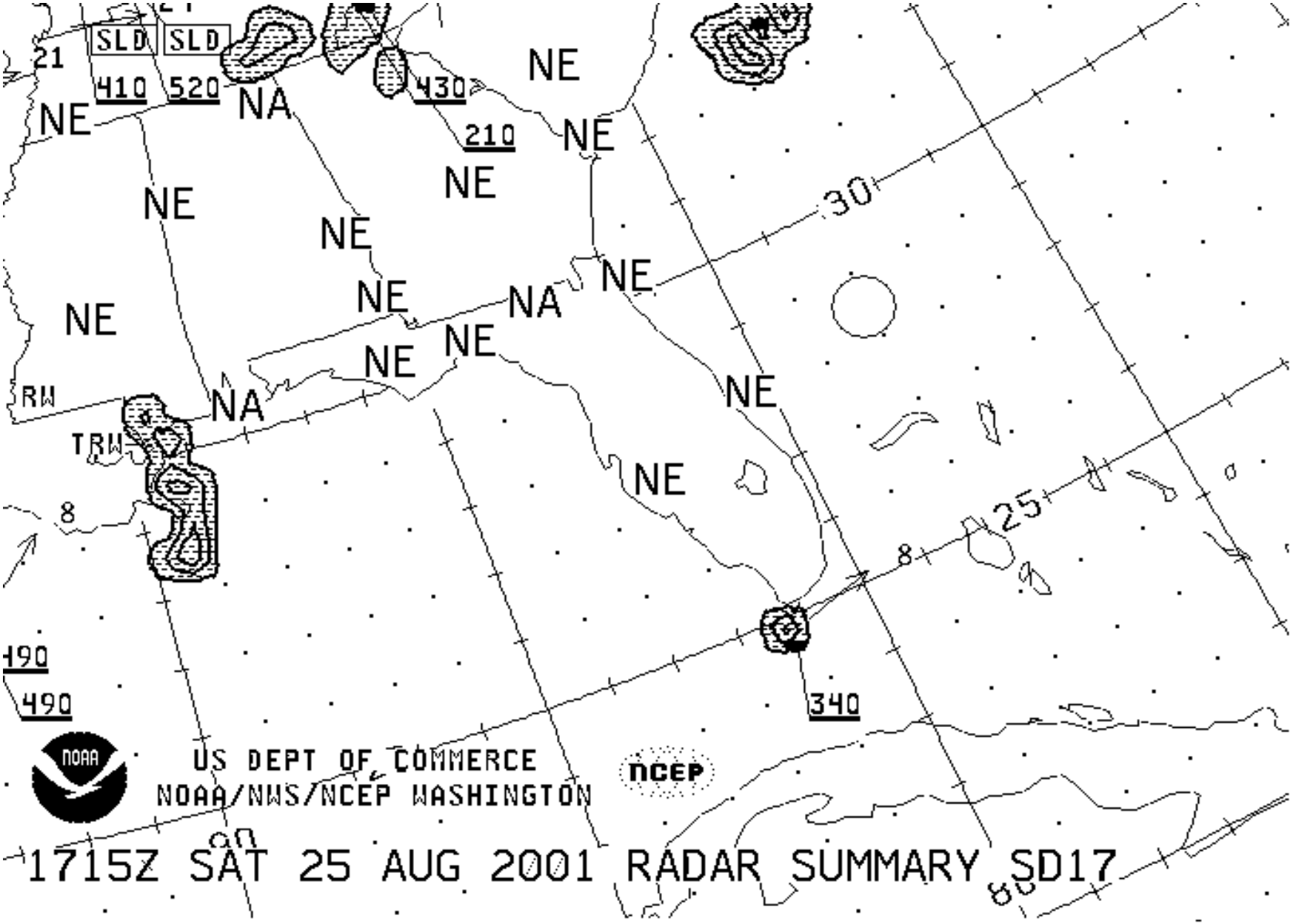
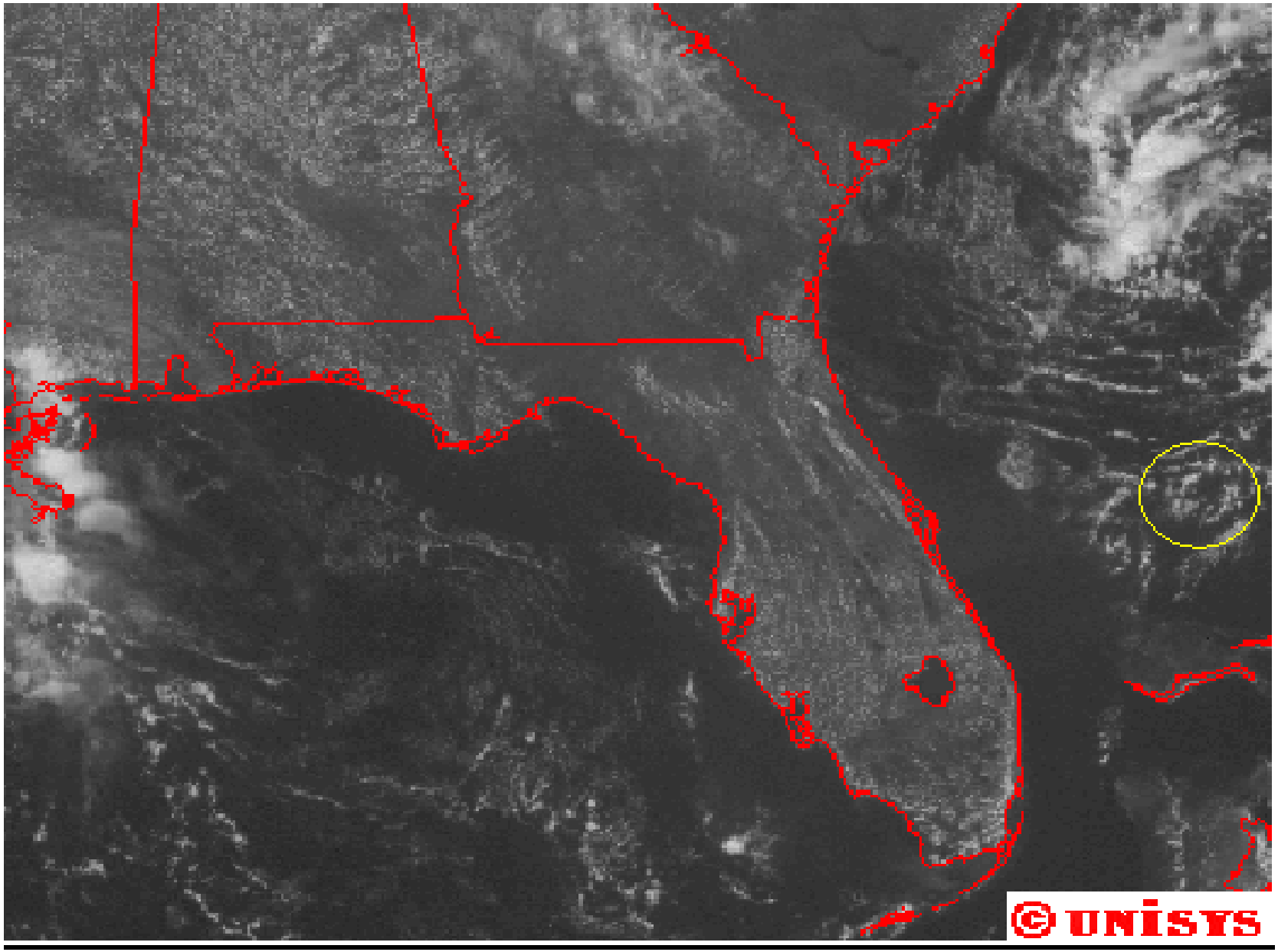
Subjective turbulence intensity rating legend:

| | | |
|---|---|---|
| > LGT | Greater than Light | peak-to-peak gust > 5 m/s, $\Delta G > 0.25$ |
| > LGT to MDT | Greater than Light to Moderate | peak-to-peak gust > 9 m/s, $\Delta G > 0.45$ |
| > MDT | Greater than Moderate | peak-to-peak gust > 13 m/s, $\Delta G > 0.65$ |

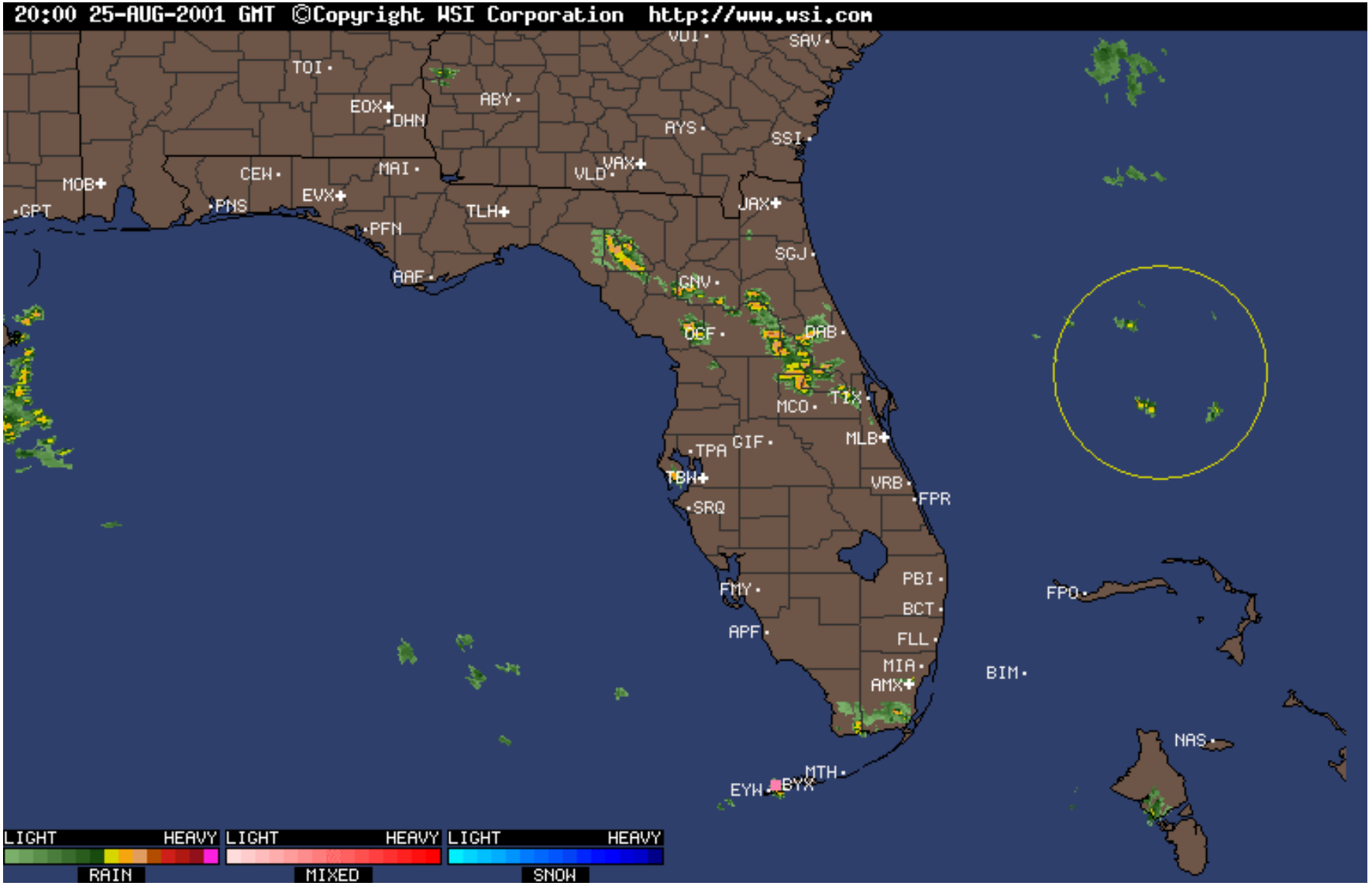
# Case 1: August 25, 2001 1715Z RADAR



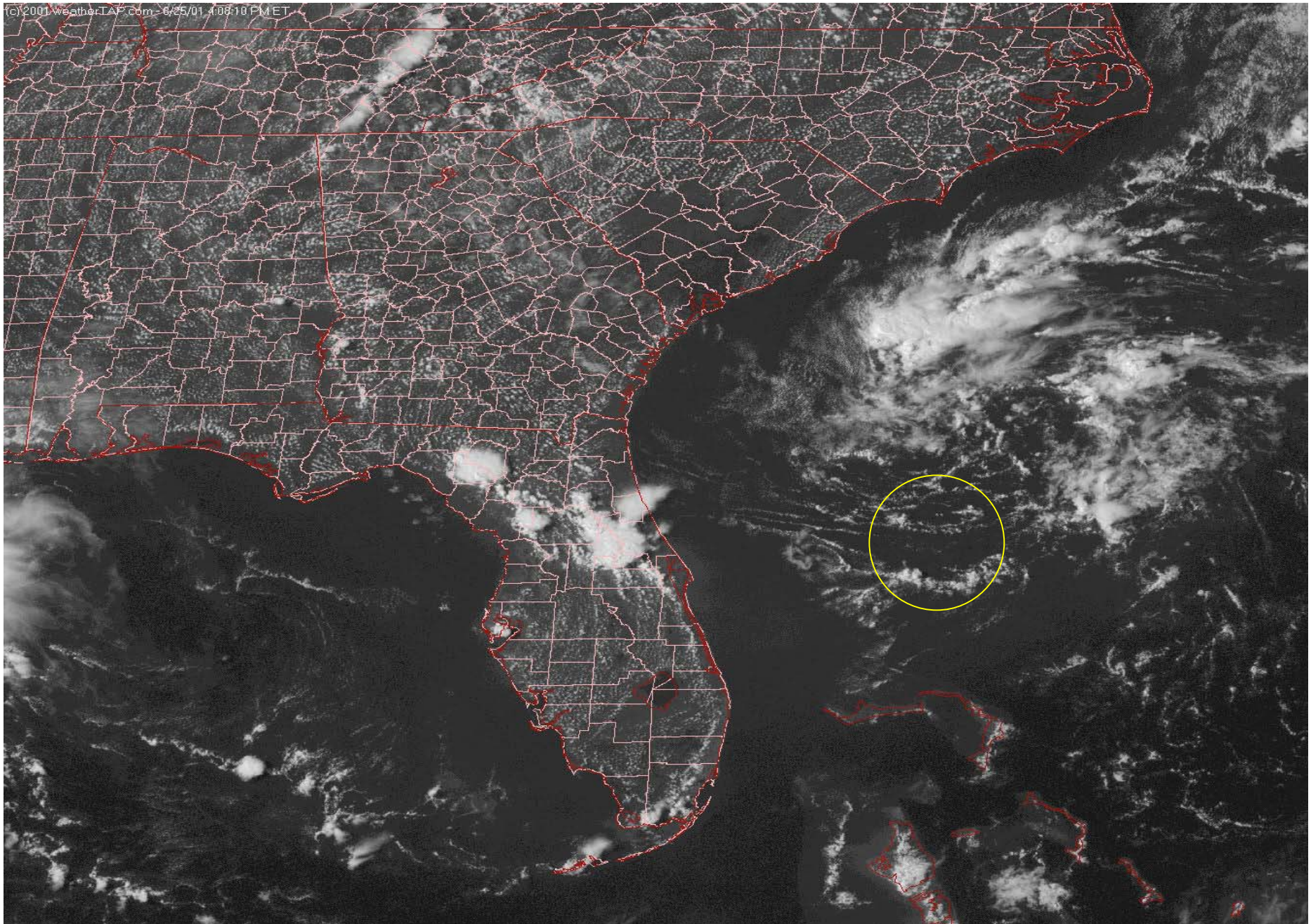
# Case 1: August 25, 2001 1730Z Visible Satellite



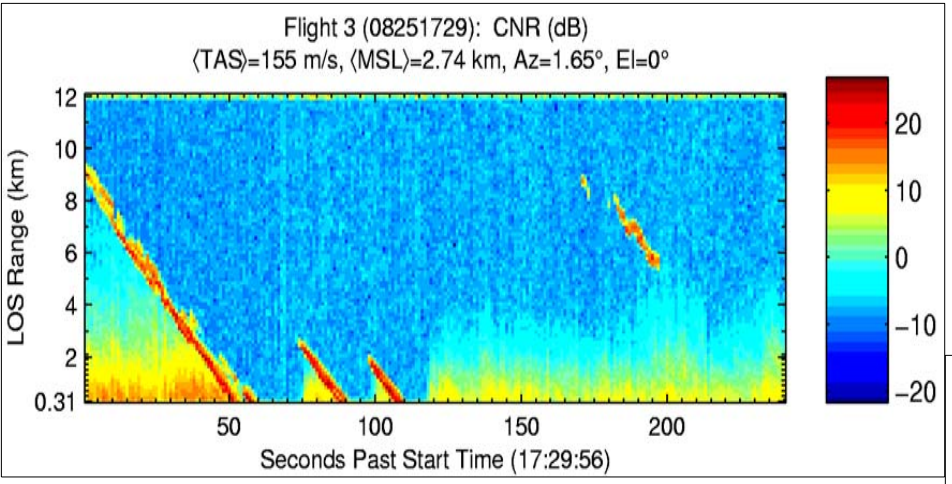
# Case 1: August 25, 2001 2000Z RADAR



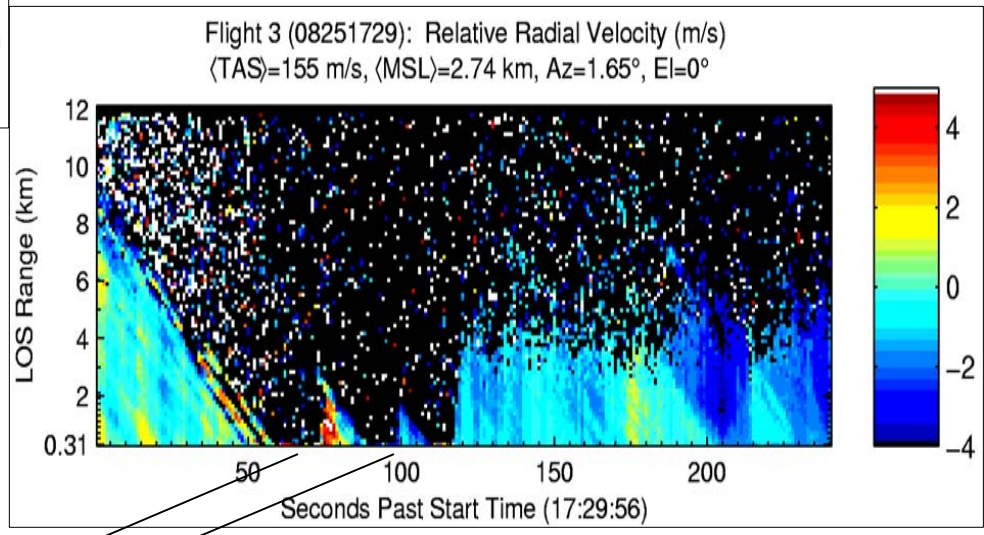
# Case 1: August 25, 2001 2008Z Visible Satellite



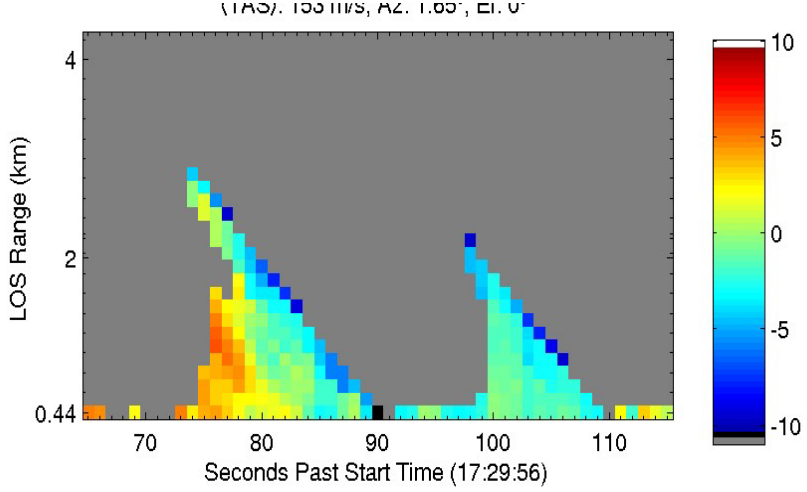
# Cloud and Gust Penetration Sample 08/25/01

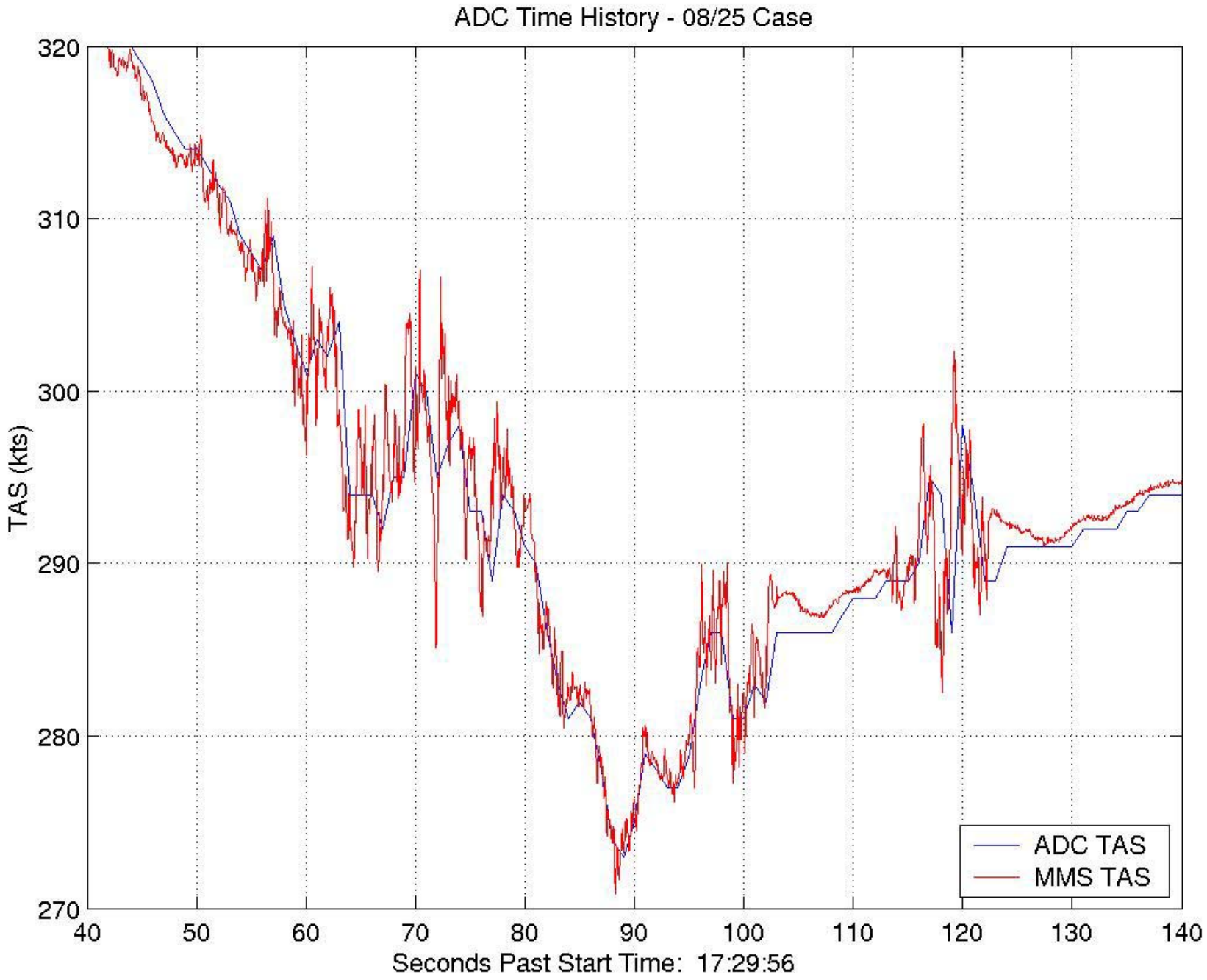


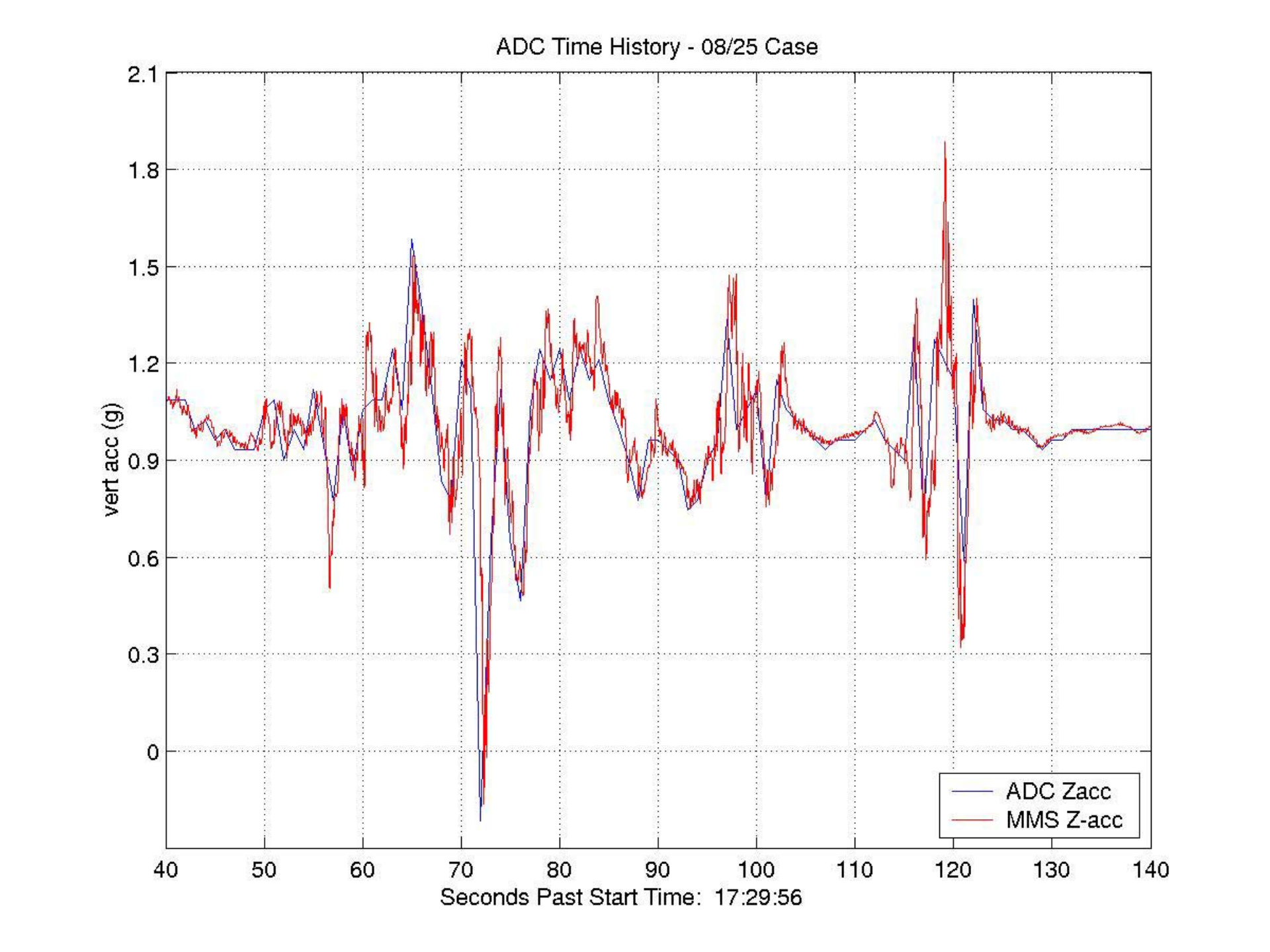

**Coherent signal-to-noise ratio**

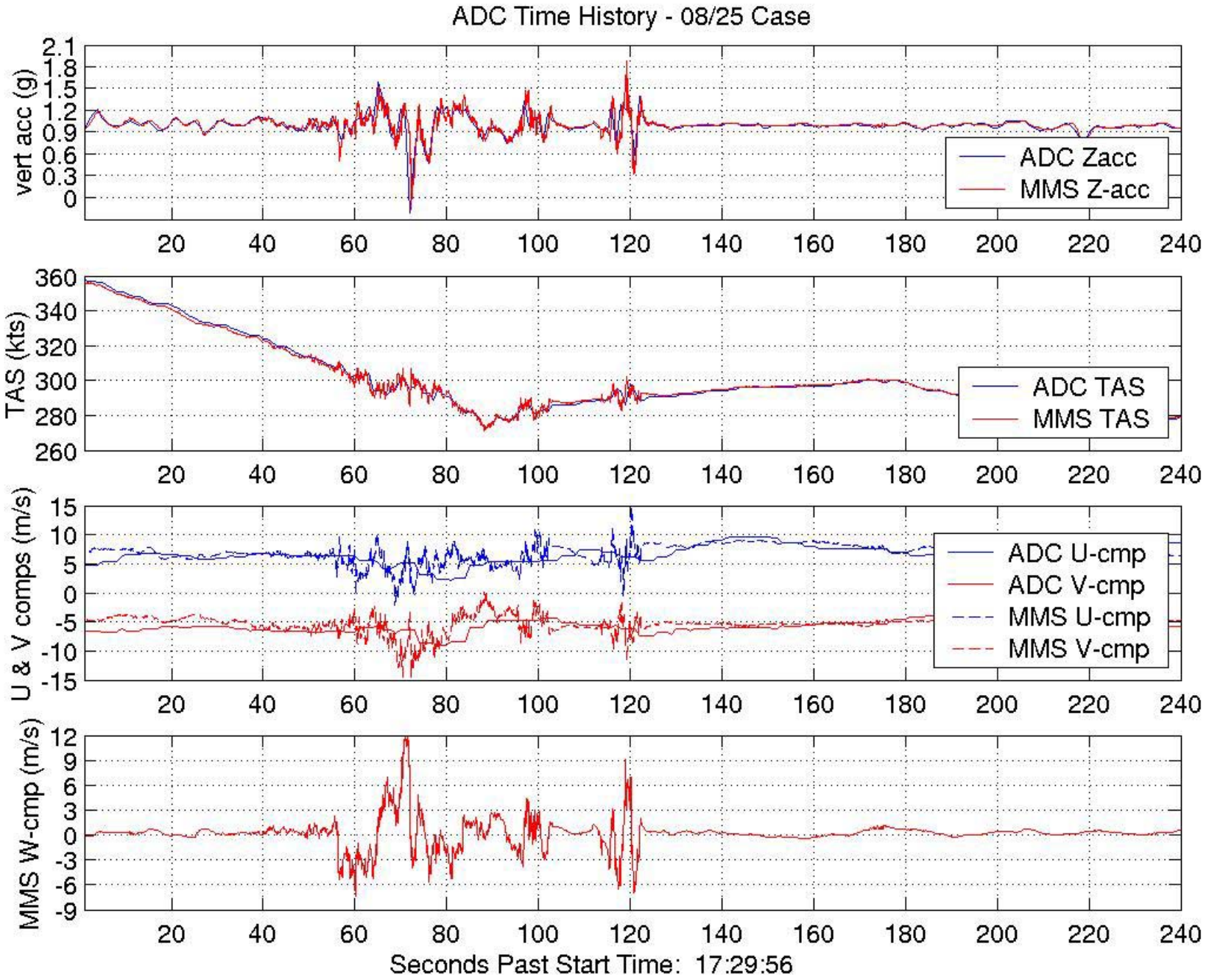



**Lidar radial velocity**

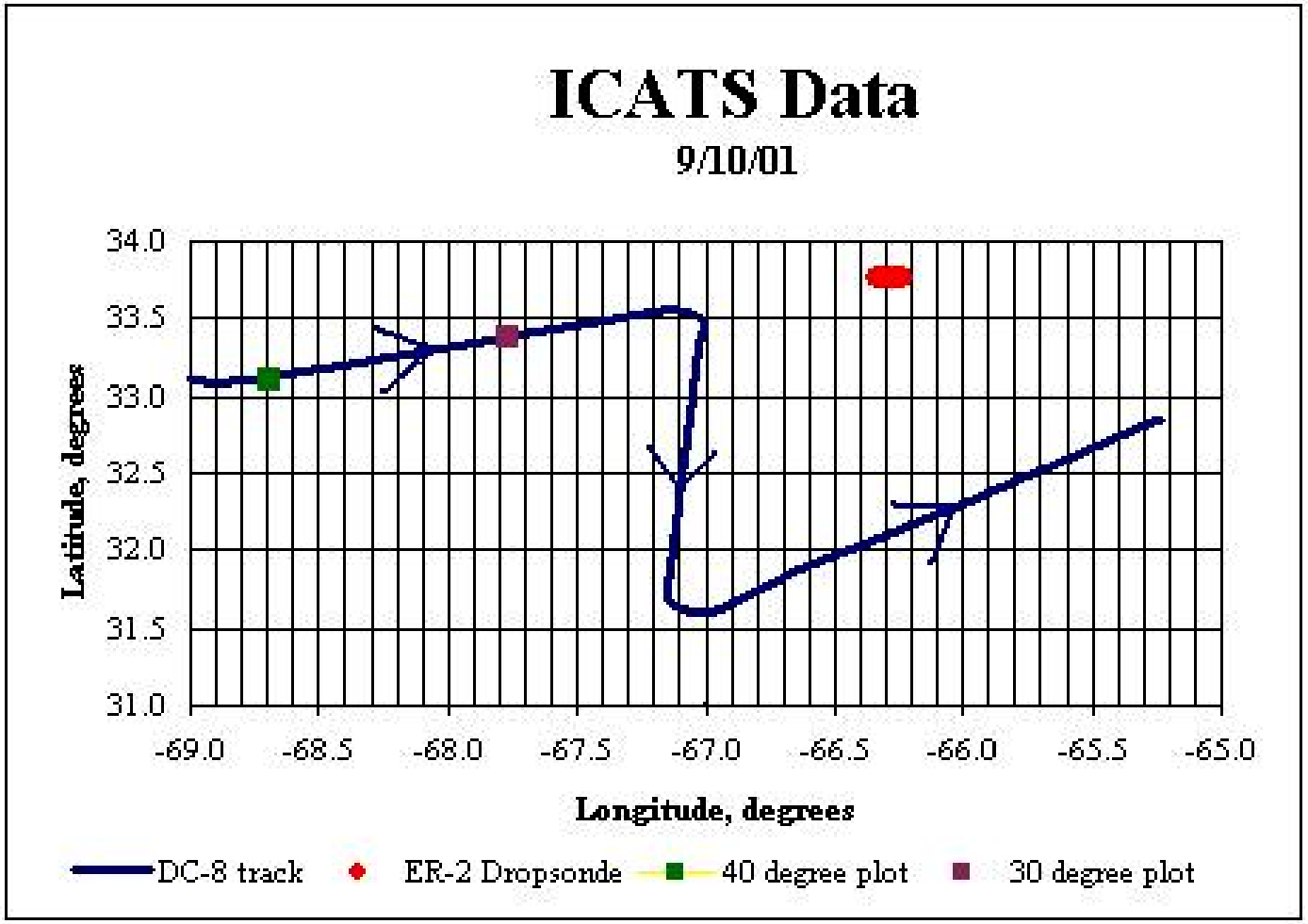



ADC Time History - 08/25 Case
TAS (kts)
320
310
300
290
280
270
40
50
60
70
80
90
100
110
120
130
140
Seconds Past Start Time: 17:29:56
ADC TAS
MMS TAS


ADC Time History - 08/25 Case
vert acc (g)
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0
40
50
60
70
80
90
100
110
120
130
140
Seconds Past Start Time: 17:29:56
ADC Zacc
MMS Z-acc

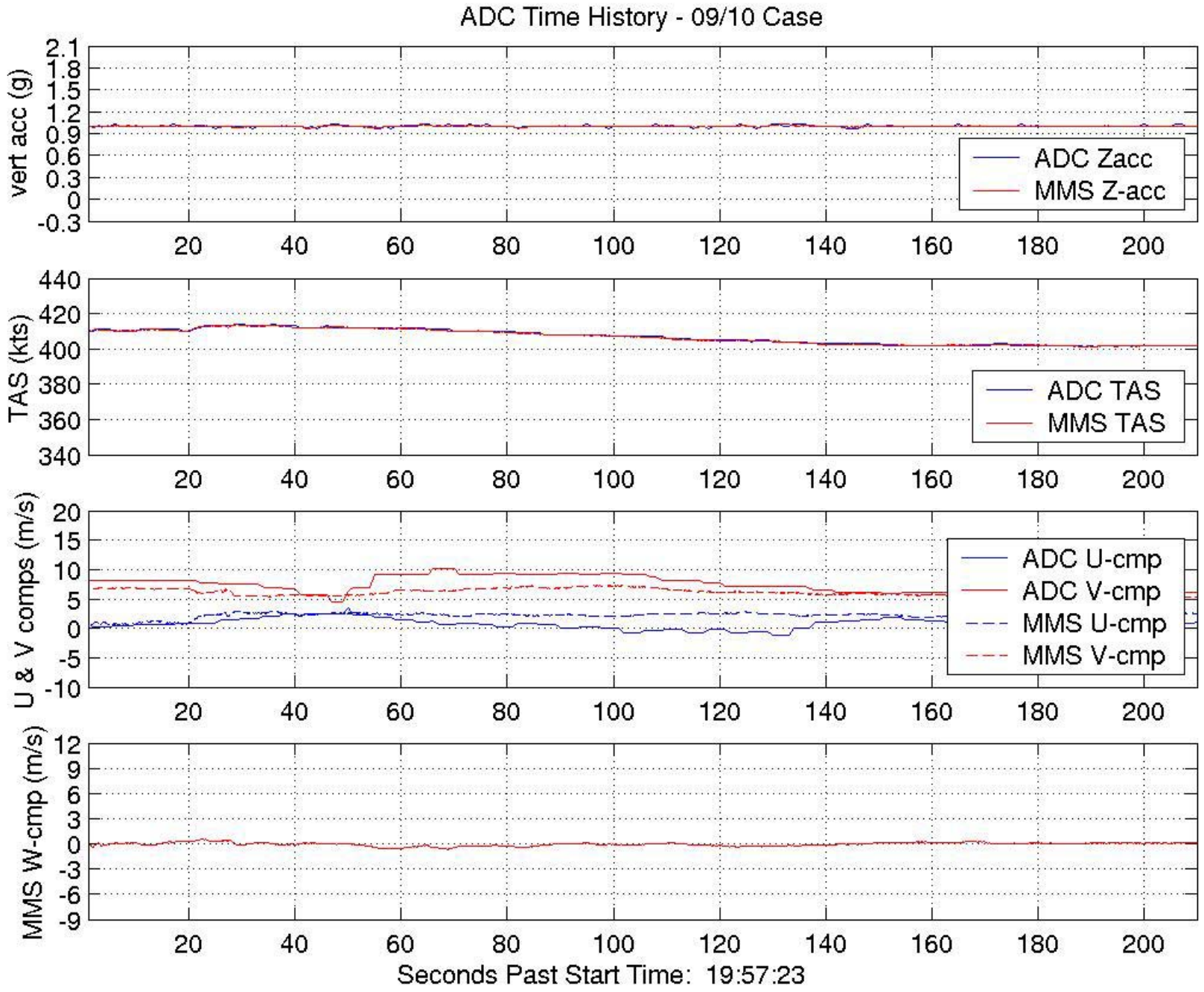

ADC Time History - 08/25 Case
vert acc (g)
ADC Zacc
MMS Z-acc
TAS (kts)
ADC TAS
MMS TAS
U & V comps (m/s)
ADC U-cmp
ADC V-cmp
MMS U-cmp
MMS V-cmp
MMS W-cmp (m/s)
Seconds Past Start Time: 17:29:56

# Case 2: September 10, 2001 DC-8 Ground Track

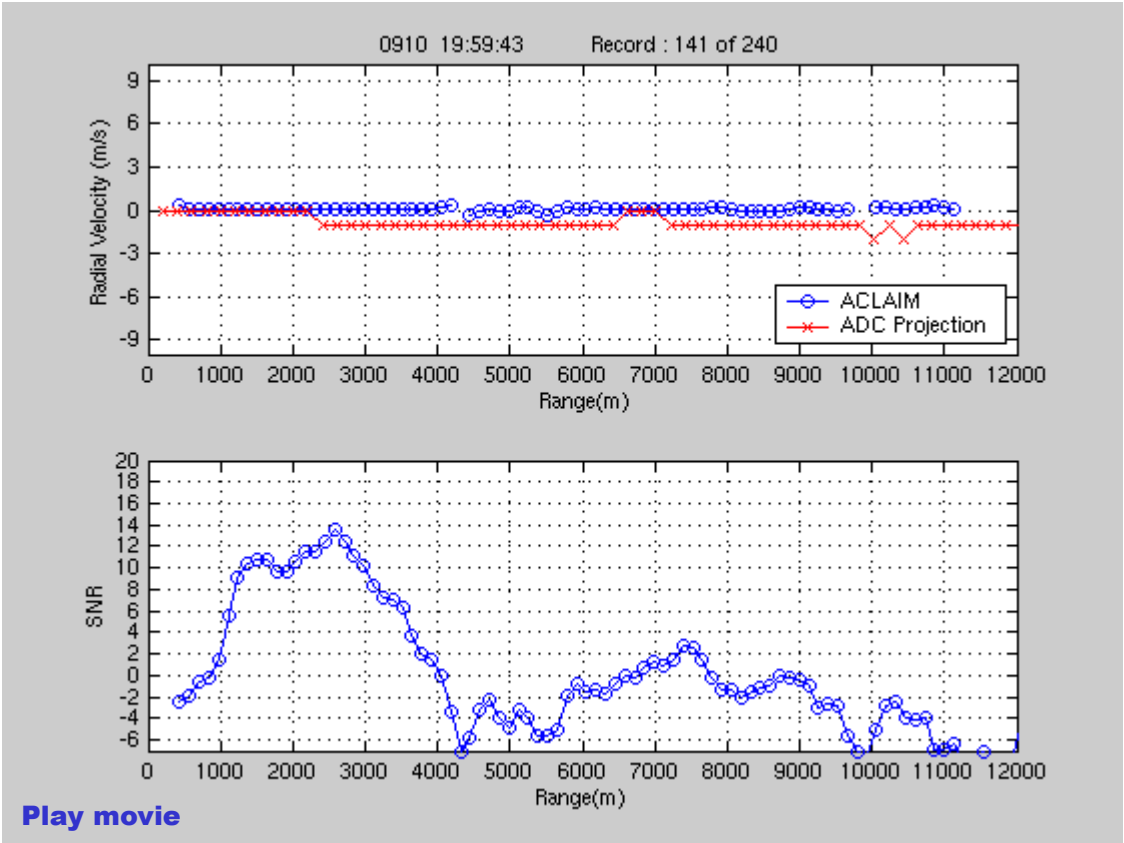



ICATS = Information Collection And Transmission System

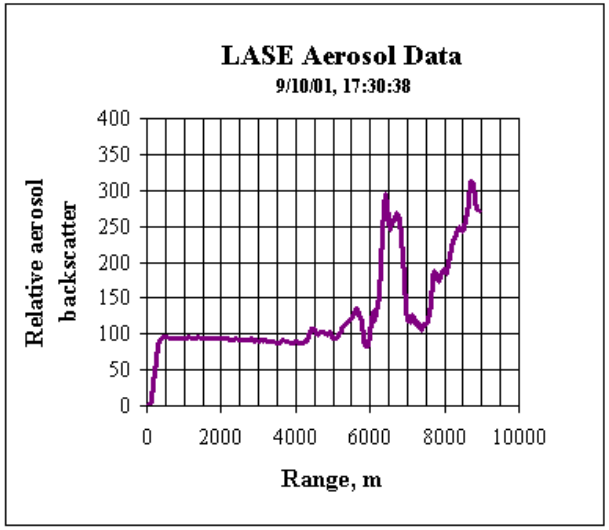
# Case 2 September 10, 2001 Lidar Velocity vs Altitude

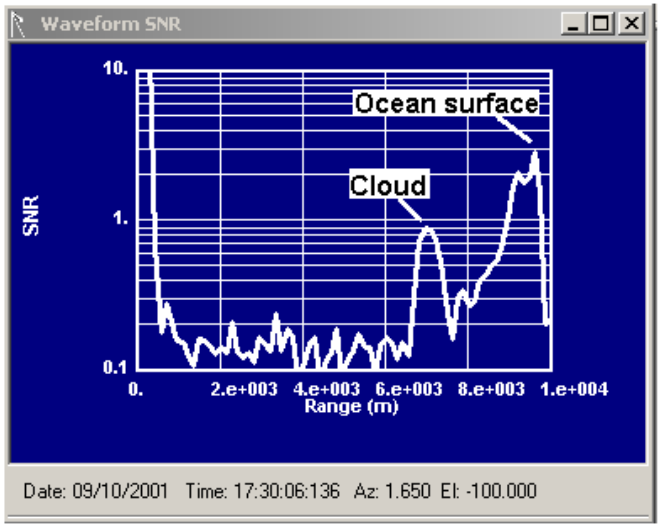

ADC Time History - 09/10 Case
vert acc (g)
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0
-0.3
ADC Zacc
MMS Z-acc
TAS (kts)
440
420
400
380
360
340
ADC TAS
MMS TAS
U & V comps (m/s)
20
15
10
5
0
-5
-10
ADC U-cmp
ADC V-cmp
MMS U-cmp
MMS V-cmp
MMS W-cmp (m/s)
12
9
6
3
0
-3
-6
-9
20
40
60
80
100
120
140
160
180
200
Seconds Past Start Time: 19:57:23

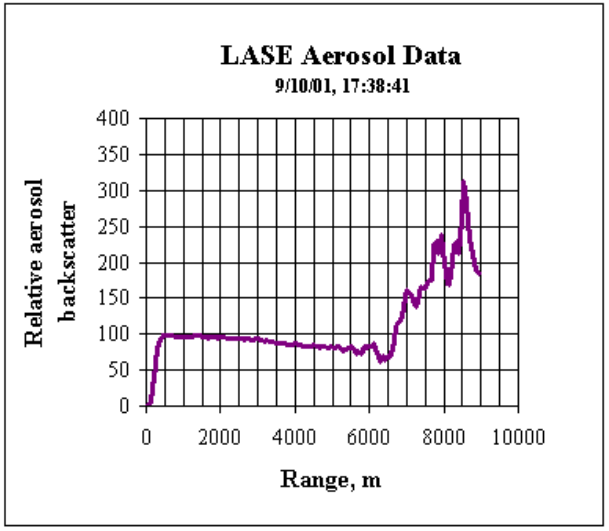
# Case 2 September 10, 2001 Lidar Velocity vs Range

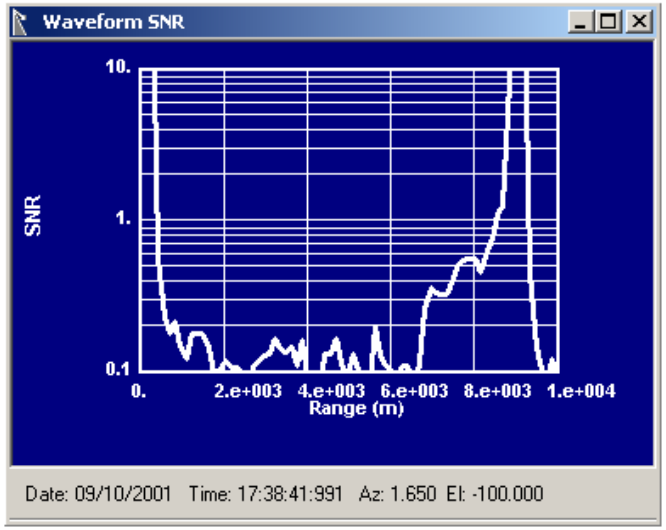


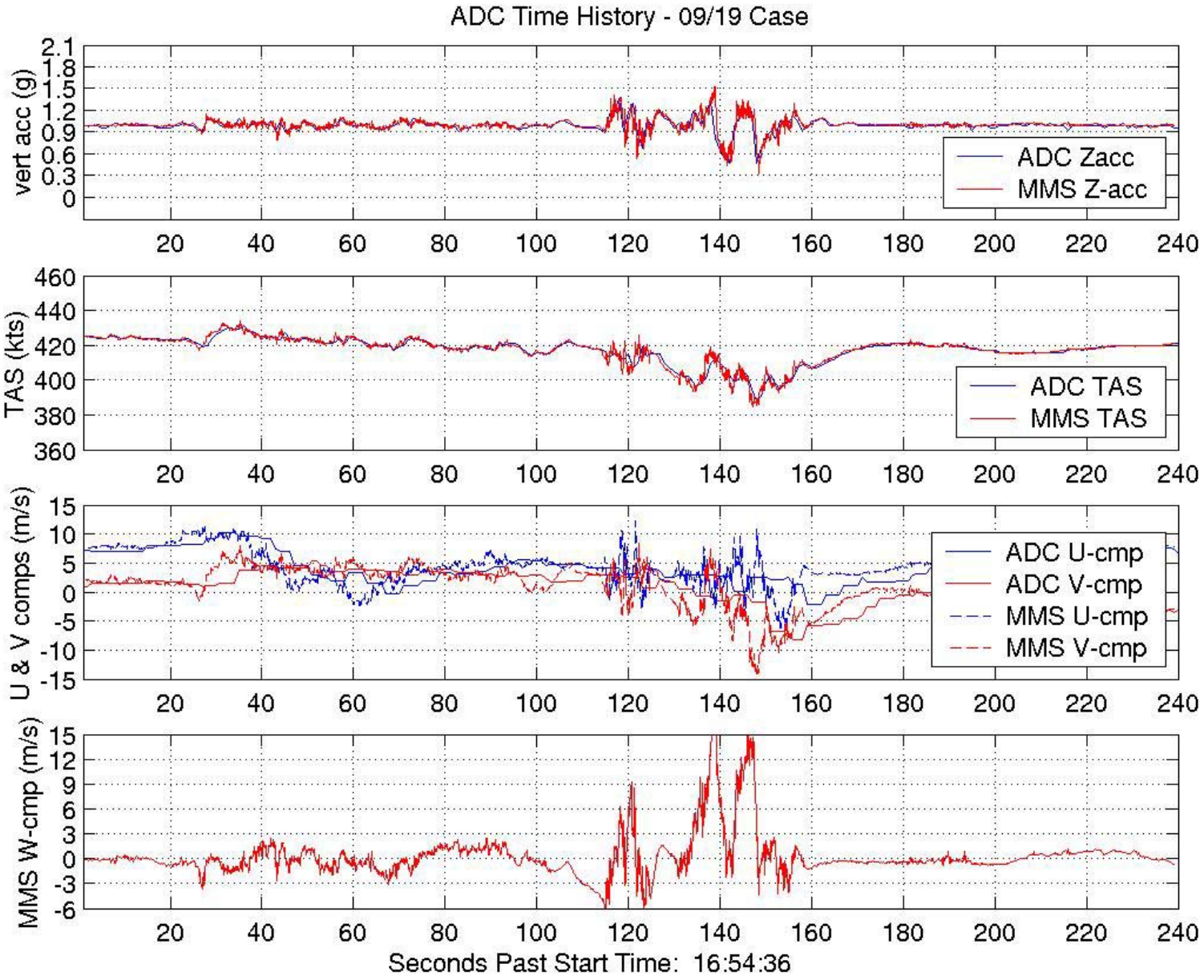
# Case 2: September 10, 2001 Down-looking Comparison Lidar Atmospheric Sensing Experiment (LASE) vs ACLAIM



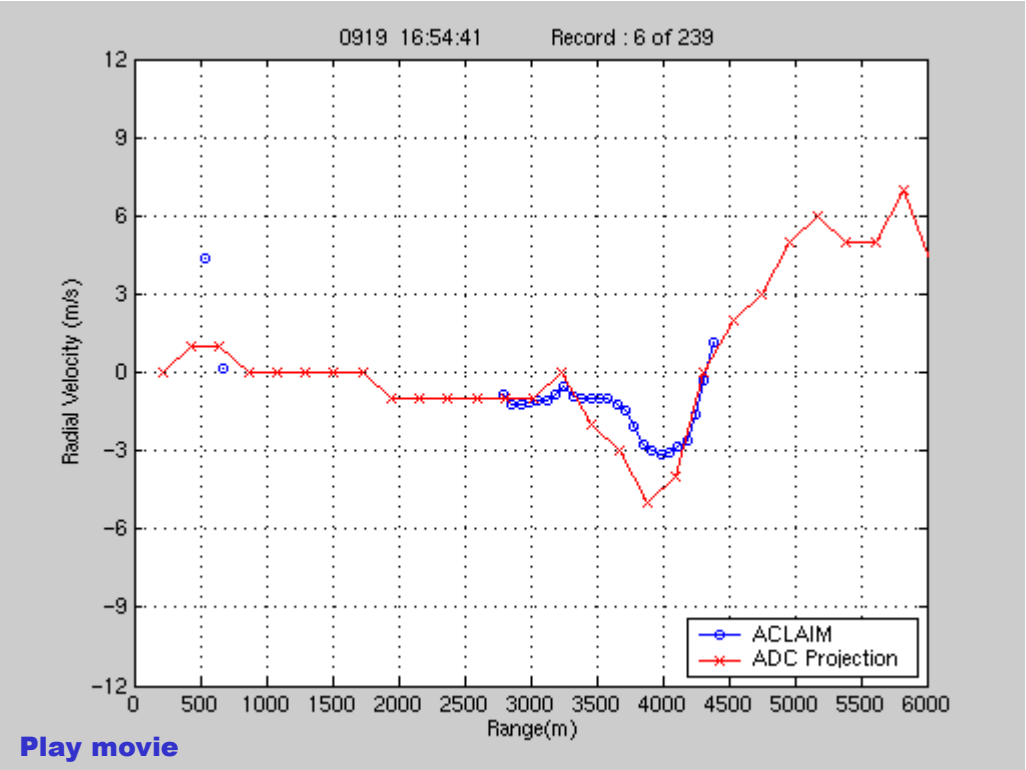



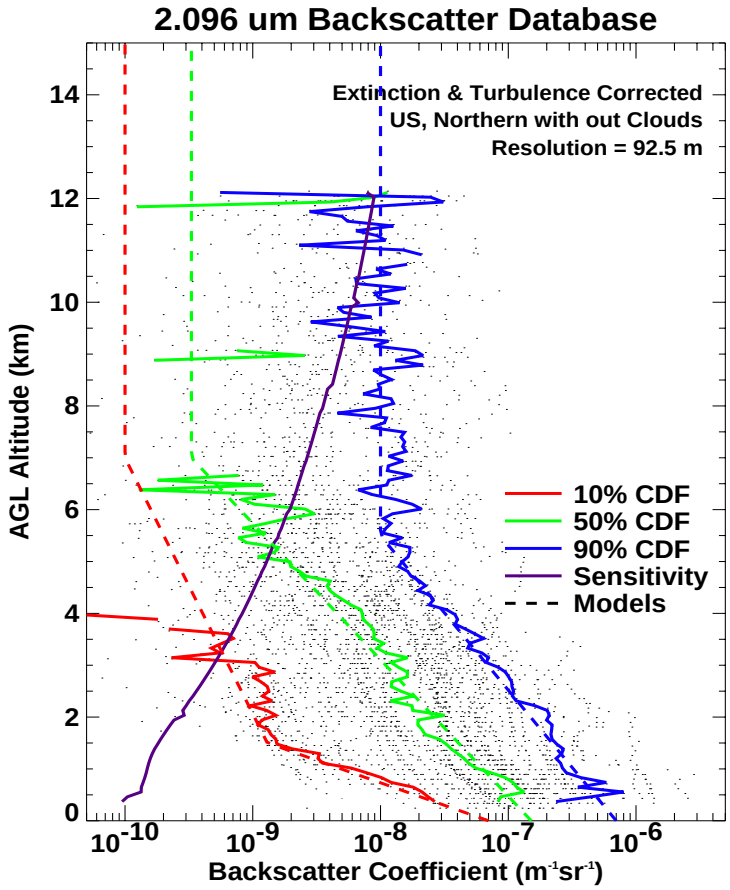

ADC Time History - 09/19 Case
vert acc (g)
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0
ADC Zacc
MMS Z-acc
TAS (kts)
460
440
420
400
380
360
ADC TAS
MMS TAS
U & V comps (m/s)
15
10
5
0
-5
-10
-15
ADC U-cmp
ADC V-cmp
MMS U-cmp
MMS V-cmp
MMS W-cmp (m/s)
15
12
9
6
3
0
-3
-6
20
40
60
80
100
120
140
160
180
200
220
240
Seconds Past Start Time: 16:54:36

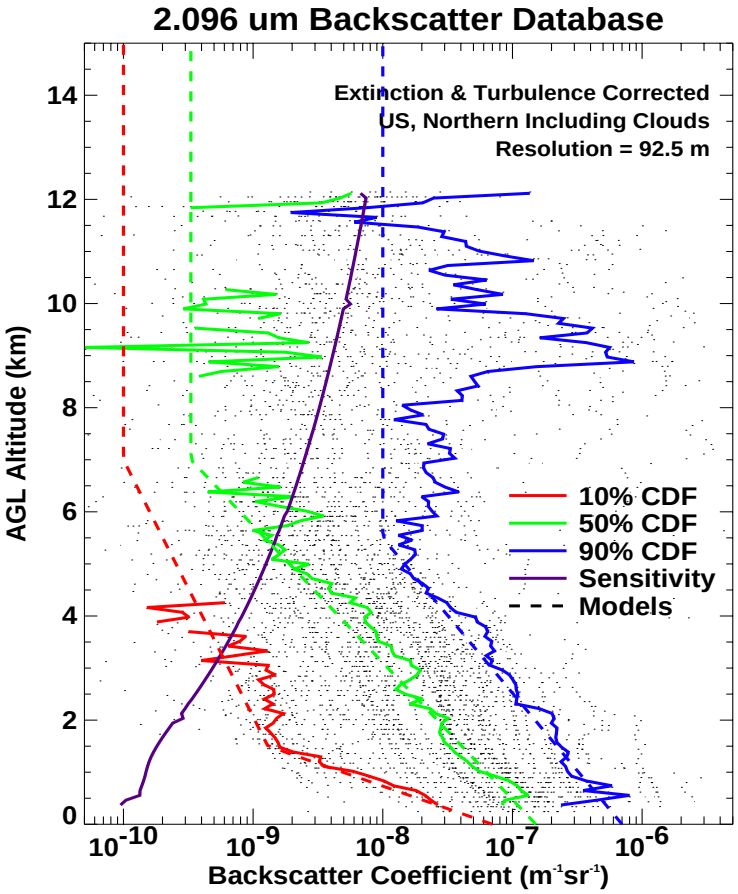
# Case 3 September 19, 2001 Lidar Velocity vs Range



# Previous 2 um Backscatter Database from Ground Measurements Lack High Altitude Data Confidence

- High altitude 50 % profile derived from GLOBE measurements at 1.06 um.

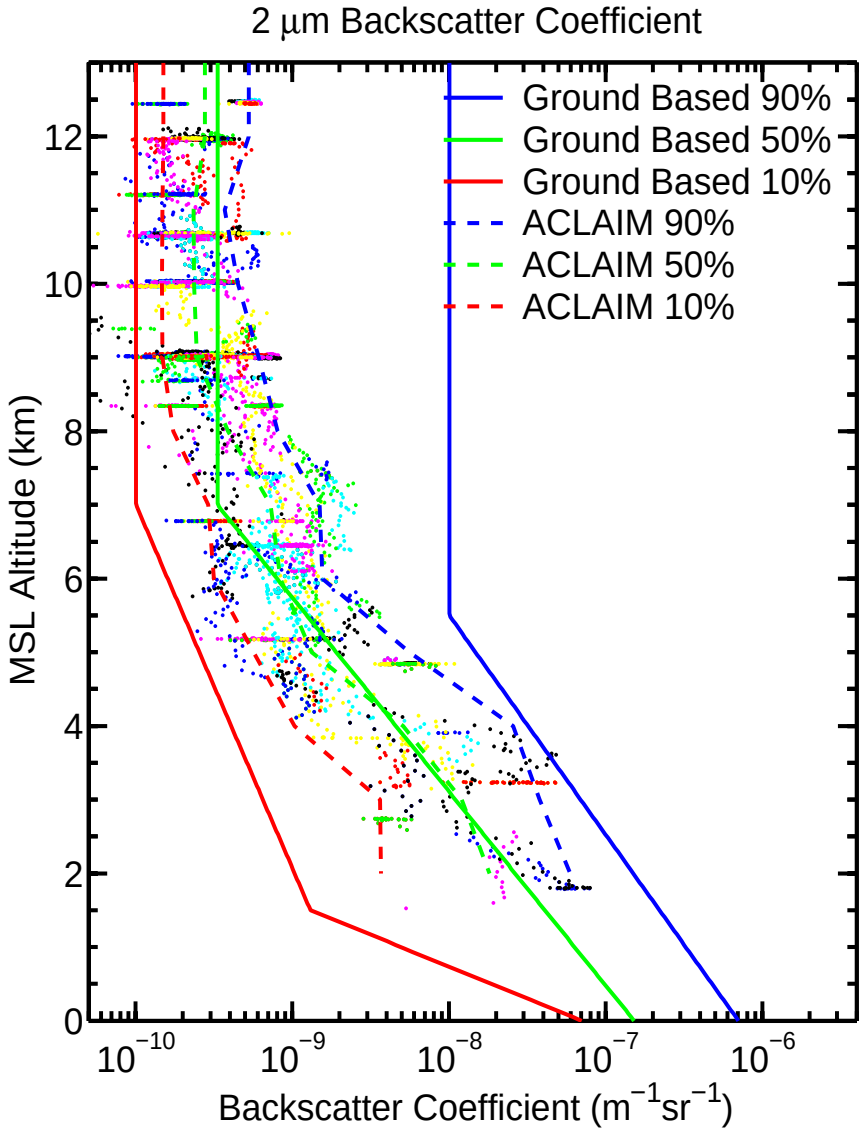



**Summary plots of 2um aerosol backscatter database collected over 1995-1996 in the continental US Sub visible cirrus produces a 20 to 30 dB enhancement.**

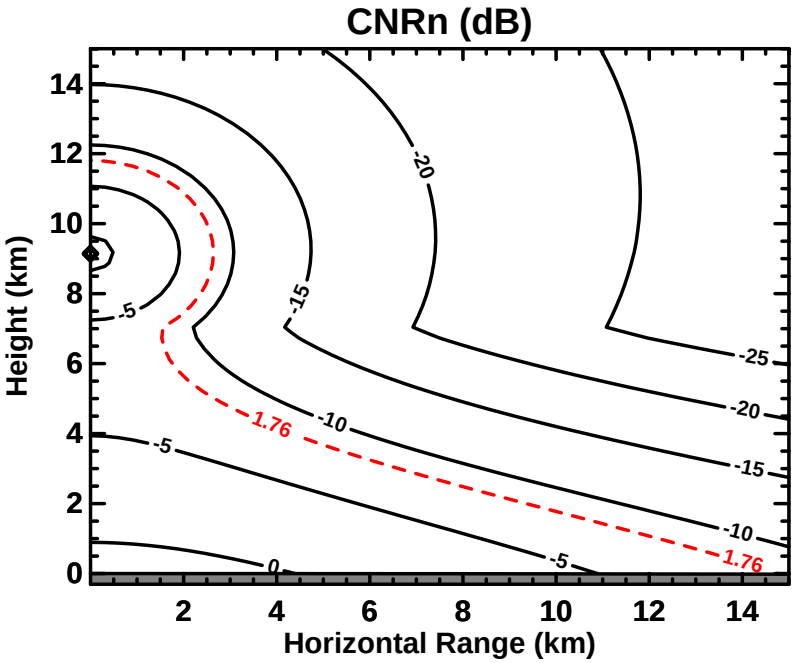
# Backscatter Data Envelope

- Approximately 5 hours (3600 5 second samples) of data (out of 40 hours of flight data) were compiled into this backscatter database.
- Forward looking data only
- Ignored cloud and sub-visible cirrus data thus using only background levels
- Ignored data when window was iced or fogged over
- Database is consistent with ground based measurements



# Range vs. Altitude Performance Predictions

CNR and maximum range (FOM = $\sqrt{N}CNRn = 1.76$ dB) for 100 pulse averages at a 30 kft platform (left) and 40 kft platform (right)



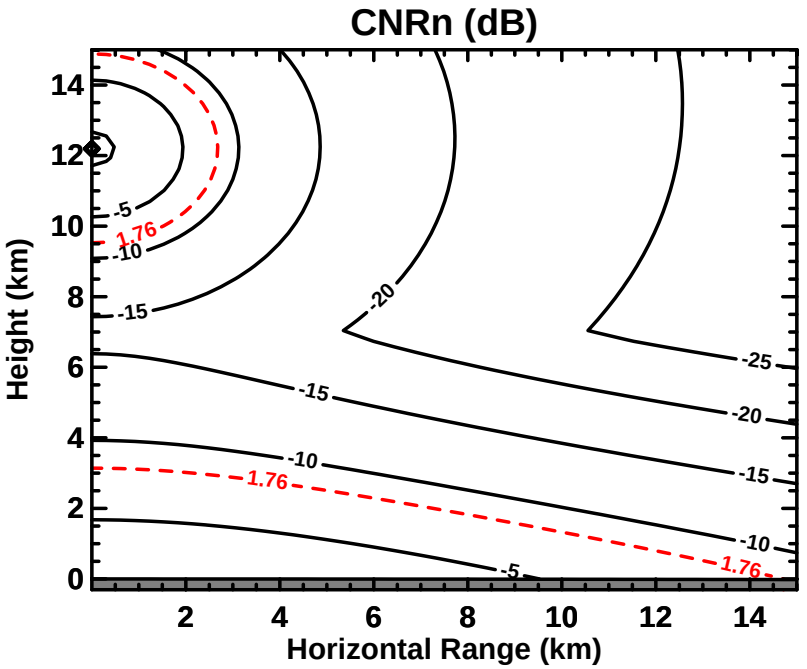

Energy: 8.000 mJ
λ: 2.012501 um
570.0 ns
TotEff: 10.0 %
PlatForm: 9.144 km
BeamDiam: 8.0 cm
Focus: 2.0 km

Target: Aerosol
BetaMod: CTI_50%
BetaMult: 1.00
BetaEnh: 0

Navg = 100
FOMmin = 1.5

Cn2Mod: HV57
Cn2_Mult: 1.00

AtmMod: MLS
HazeMod: Rural 23km
Vis: Default




Energy: 8.000 mJ
λ: 2.012501 um
570.0 ns
TotEff: 10.0 %
PlatForm: 12.192 km
BeamDiam: 8.0 cm
Focus: 2.0 km

Target: Aerosol
BetaMod: CTI_50%
BetaMult: 1.00
BetaEnh: 0

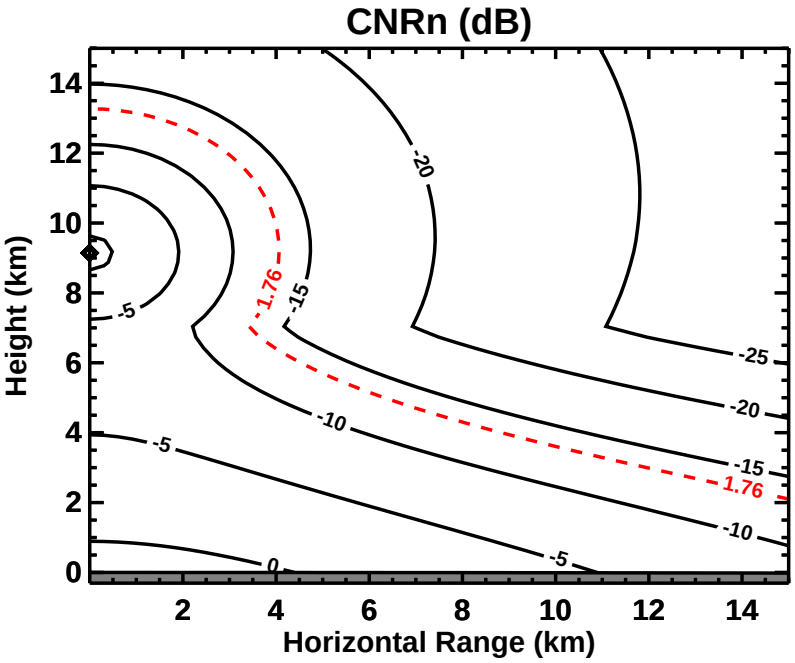
Navg = 100
FOMmin = 1.5

Cn2Mod: HV57
Cn2_Mult: 1.00

AtmMod: MLS
HazeMod: Rural 23km
Vis: Default

# Range vs. Altitude Performance Predictions

CNR and maximum range (FOM = $\sqrt{N}CNRn$ = 1.76 dB) for 1000 pulse averages at a 30 kft platform (left) and 40 kft platform (right)



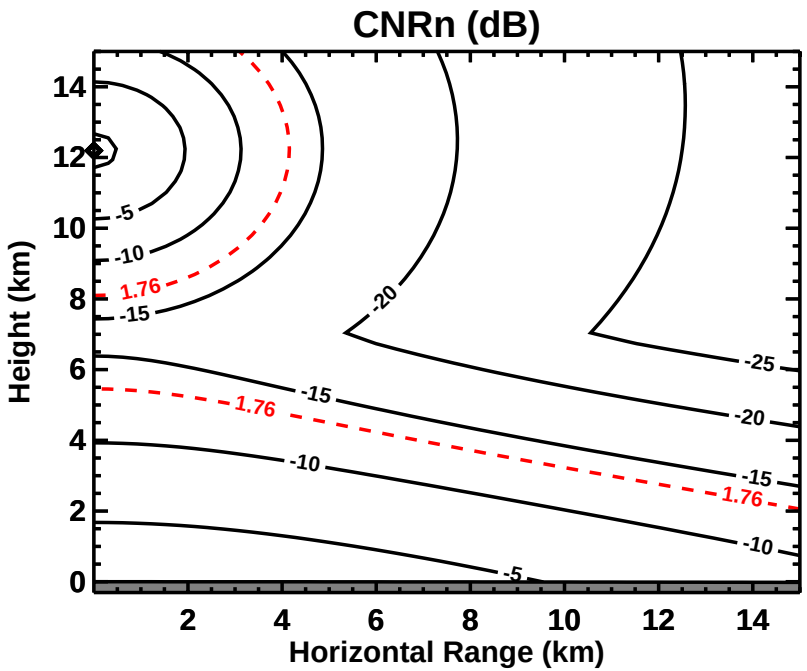

Energy: 8.000 mJ
λ: 2.012501 um
570.0 ns
TotEff: 10.0 %
PlatForm: 9.144 km
BeamDiam: 8.0 cm
Focus: 2.0 km

Target: Aerosol
BetaMod: CTI_50%
BetaMult: 1.00
BetaEnh: 0

Navg = 1000
FOMmin = 1.5

Cn2Mod: HV57
Cn2_Mult: 1.00

AtmMod: MLS
HazeMod: Rural 23km
Vis: Default




Energy: 8.000 mJ
λ: 2.012501 um
570.0 ns
TotEff: 10.0 %
PlatForm: 12.192 km
BeamDiam: 8.0 cm
Focus: 2.0 km

Target: Aerosol
BetaMod: CTI_50%
BetaMult: 1.00
BetaEnh: 0

Navg = 1000
FOMmin = 1.5

Cn2Mod: HV57
Cn2_Mult: 1.00

AtmMod: MLS
HazeMod: Rural 23km
Vis: Default

# Aviation Safety Program
## Technical Accomplishment

**Accomplishment:**

- The Lidar system CAMEX-4 flight demonstration gathered information about the Lidar performance in high atmospheric moisture conditions. This information is critical to assess the usability of the Lidar technology in the role of turbulence detection and to understand the Lidar contribution as an element in a multi-sensor comprehensive turbulence prediction and warning system
- Gathered doppler velocity and 2-micron atmospheric backscatter data for high altitude clear-air cruise conditions.
- Showed the utility of 2-micron Lidar in and through light cloud conditions.

**Plans:**

- Continue evaluation of flight data and assessment of Lidar performance in related flight environments to refine and solidify the Lidar role in turbulence prediction and warning systems.

**Lidar Benefits:**

- Lidar technology enables the detection of turbulence in situations where there are no visual cues (clear air) or weather radar returns to indicate its presence

# Flight Conditions Encountered by the 2-micron ACLAIM Lidar during CAMEX-4

**Closing Remarks**

- **Sampled a wide range of in-cloud and clear-air lidar beam-path distances (55 hrs)**
- **Documented clear-air 2-micron backscatter experience**
- **Lidar and airplane true airspeed data agree**
- **ACLAIM successfully detected wind shear and gust perturbations at ranges up to 12 km**
- **Missions provided exposure to a wide operational environment**
- **Potential lidar applications beyond turbulence prediction include gust component and wind shear detection**

# Acknowledgements


- NASA Aviation Safety Program
- Numerous DOD and NASA collaborators who assisted in the ACLAIM design and fabrication
- Co-authors, ACLAIM ground support team and DC-8 personnel
- NASA Airborne Sciences
- CAMEX-4 science team members


NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC99-45225-1 Date: October 1999 Photo by: Jim Ross

Lockheed ER-2 #809 high altitude research aircraft in flight

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC99-44896-13 Date: February 1999 Photo by: Jim Ross

DC-8 Airborne Laboratory in flight during research mission - view from above